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**STATIC TESTS OF CORROSION INHIBITORS
FOR ALUMINUM AND CARBON STEEL**

JANUARY 1965

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STATIC TESTS OF CORROSION INHIBITORS
FOR ALUMINUM AND CARBON STEEL

By

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STATIC TESTS OF CORROSION INHIBITORS FOR ALUMINUM AND CARBON STEEL

INTRODUCTION

^{stays} / Corrosion of aluminum and carbon steel surfaces in the single-pass cooled Hanford reactors must be continuously controlled to minimize shut-down periods for repair and to eliminate costly equipment replacements. The older production reactors at Hanford are cooled with treated Columbia River water. Carbon steel is used for piping and structural members in the water treatment and storage systems, and in the piping systems that supply treated water to the nuclear reactors. Aluminum is used for coolant tubes in the reactors, and for cladding on the nuclear fuel elements. The cooling water must be treated primarily to minimize corrosion of the aluminum components and at the same time maintain control of carbon steel corrosion in the rapidly flowing water. In addition, a reduction of carbon steel corrosion under static cold-water conditions is desirable in other parts of the Hanford water systems. ^{al, ss} Sodium dichromate is presently used to inhibit corrosion of both aluminum and steel in most of the Hanford water systems. /

The experiments described in this report were performed for two purposes: (1) to find a chemical, or combination of chemicals, that would be effective for inhibiting corrosion of steel in static portions of the Hanford water systems, and (2) as screening tests to select candidate mixtures for further testing to replace sodium dichromate as the inhibitor of aluminum and steel corrosion in the Hanford single-pass reactor cooling water.

SUMMARY AND CONCLUSIONS

Uniform corrosion losses and pitting tendencies were measured for carbon steel and aluminum samples exposed for as long as 9 1/2 months at ambient temperature in static, nonrefreshed solutions of 38 different inhibitor mixtures. [TABLE I]

Results from these tests indicate that two inhibitors: (1) ^{al, ss} sodium hexameta-phosphate, and (2) ^{al, ss} sodium nitrite plus sodium silicate, are possible

✓ candidates to replace sodium dichromate in dynamic or static systems that contain both carbon steel and aluminum. Three additional inhibitors reduced the uniform corrosion of carbon steel. Limited measurements of inhibitor depletion were obtained, but the effects of this depletion on corrosion were not defined.

Candidate mixtures should be tested in dynamic systems at temperatures typical of Hanford reactor operation, to confirm the indications of satisfactory corrosion inhibition shown by these static tests.

DISCUSSION

Previous Work

Studies of corrosion in different aqueous systems at Hanford have been conducted in laboratories, pilot plants, and full-scale systems since the beginning of the Manhattan Project in World War II. ⁽¹⁻⁴⁾ These studies have usually included tests of corrosion inhibitors; i. e., materials added to the water to reduce corrosion of various metal surfaces exposed to the water. Early work at Hanford, summarized by C. P. Kidder, ⁽¹⁾ evaluated different methods for prevention of corrosion and film deposition on aluminum and steel surfaces in treated Columbia River water. On the basis of these early studies, sodium dichromate was added to the filtered water to reduce corrosion, and sodium silicate was added to reduce film deposition on aluminum surfaces in the nuclear reactors. Various studies have been conducted since that time, with the aim of reducing the amount of chemical usage. ⁽³⁾ Reduction of sodium dichromate addition was a particular goal, because of the cost of this chemical, and because of a continuing desire to reduce the amount of both hexavalent chromium and radioactive Cr^{51} which are released to the Columbia River from the Hanford plants. Efforts to reduce chemical usage were successful for the silicate but only partly successful for dichromate. Sodium silicate addition was terminated, after accumulated operating experience showed that satisfactorily low film levels could be maintained without it. Later improvements in Hanford water treatment have provided fully satisfactory control of film deposition in the nuclear reactors.

Continued testing, both in- and out-of-reactor, as well as operating experience, have shown that some kind of chemical inhibition of Hanford process water is required. ⁽³⁾ Some reduction in sodium dichromate concentration has been achieved, but a concentration ranging between 1.0 and 1.8 ppm is still used.

Criteria for Selection of Candidate Materials for Testing

The materials to be tested (Table I) were mixtures for the most part, and were selected on the basis of consistent effectiveness indicated by other studies, radioactivation properties, and cost. Many mixtures of chemicals were included in this test program, but only a few single chemicals were tested as replacements for the sodium dichromate, since dichromates are usually found to be superior to other single chemicals for the simultaneous inhibition of aluminum and steel corrosion in natural waters. ⁽⁵⁾ Chemical mixtures are more promising as dichromate replacements, because chemicals used in combination often have synergistic properties that far exceed the effectiveness of either chemical alone.

TABLE I


CANDIDATE INHIBITOR MIXTURES TESTED

Note: All concentrations total 100 ppm (50 + 50 ppm) except as noted.

Exposure A (9 month total)

1. Sodium nitrite (NaNO_2)
2. Sodium dichromate ($\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$)
3. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}:1.58 \text{ SiO}_2$)
4. Sodium nitrite plus sodium sulfite (Na_2SO_3)
5. Sodium sulfite plus $\text{Na}_2\text{O}:1.58 \text{ SiO}_2$
6. Sodium glucosate
7. Sodium chrome glucosate
8. Empty
9. Proprietary filming amine, A
10. Sodium dichromate plus chromium nitrate [$\text{Cr}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$]
(Ratio of Cr^{+6} to Cr^{+3} = 7.5; total chromium = 35 ppm)
11. Sodium benzoate

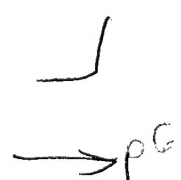
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12. Sodium benzoate plus sodium nitrite
 13. Sodium dichromate plus $\text{Na}_2\text{O}: 1.58 \text{ SiO}_2$
 14. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 3.25 \text{ SiO}_2$)
 15. Sodium sulfite plus $\text{Na}_2\text{O}: 3.25 \text{ SiO}_2$
 16. Sodium nitrite plus sodium metasilicate ($\text{Na}_2\text{SiO}_3 \cdot 9 \text{ H}_2\text{O}$)
 17. Sodium hexametaphosphate [$(\text{NaPO}_3)_6$]
 18. Sodium nitrite

Exposure B (9.5 months total)

19. None (filtered water alone)
20. Sodium dichromate
21. Sodium nitrite
22. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 2.50 \text{ SiO}_2$)
23. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 1.97 \text{ SiO}_2$)
24. Sodium sulfite plus $\text{Na}_2\text{O}: 2.50 \text{ SiO}_2$
25. Sodium sulfite plus $\text{Na}_2\text{O}: 1.97 \text{ SiO}_2$
26. Proprietary formulation containing sodium nitrite
27. Morpholine (Diethylene imide oxide)
28. Proprietary filming amine, B

Exposure C (8.3 months total)

29. None (filtered water alone)
 30. Sodium dichromate
 31. Sodium nitrite
 32. Sodium sulfite
 33. 90 parts sodium benzoate plus 10 parts sodium nitrite
 34. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 0.97 \text{ SiO}_2$)
 35. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 1.58 \text{ SiO}_2$)
 36. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 1.97 \text{ SiO}_2$)
 37. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$)
 38. Sodium nitrite plus sodium silicate ($\text{Na}_2\text{O}: 3.5 \text{ SiO}_2$)
 39. Sodium sulfite plus $\text{Na}_2\text{O}: 0.97 \text{ SiO}_2$
 40. Sodium sulfite plus $\text{Na}_2\text{O}: 1.58 \text{ SiO}_2$
 41. Sodium sulfite plus $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$
 42. Sodium sulfite plus $\text{Na}_2\text{O}: 3.5 \text{ SiO}_2$
 43. Hydrogen peroxide plus $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$
- 

Exposure D (5 months total)

44. None (filtered water alone, SiO_2 content 6 ppm)
45. Sodium silicate ($\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$), to make 10 ppm added SiO_2
46. $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$, to make 15 ppm added SiO_2
47. $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$, to make 20 ppm added SiO_2
48. $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$, to make 25 ppm added SiO_2
49. $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$, to make 50 ppm added SiO_2
50. $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$, to make 100 ppm added SiO_2
51. $\text{Na}_2\text{O}: 3.2 \text{ SiO}_2$, to make 200 ppm added SiO_2
52. Sodium dichromate
53. Sodium nitrite

end
~~STAR~~

Handbooks and corrosion report literature provide much helpful information on the selection of suitable inhibitors for specific applications, but there is no adequate substitute for actual testing of proposed materials in the specific environments in which they will be used. Specific materials have been used for many years as additives to aqueous systems to reduce the corrosion of different metal surfaces.⁽⁵⁾ Successful use of an inhibitor in one water system does not guarantee even partial success in using that same inhibitor in another system. Subtle variations in water quality, natural chemical constituents, etc., are important in determining the effectiveness of any specific inhibitor, as well as are the more clearly defined variables of temperature, pH, and flow.

Radioisotope formation and neutron absorption place additional limitations on the selection of inhibitors for nuclear systems, beyond the limitations of cost, toxicity, etc., that apply to other systems. Coolant radioactivation is especially important in Hanford single-pass reactors because the reactor effluent is eventually returned to the Columbia river. Phosphate materials, known to inhibit carbon steel corrosion in most aqueous systems, are unattractive because of the production of the biologically significant radioisotope P^{32} . Borate materials, also inhibitive, are undesirable because of the significant neutron absorbing (or "poisoning" properties of B^{10} .

The cost of inhibitor chemicals is especially important for the single-pass cooled reactors because of the large amounts of chemicals required to treat the very large quantities of single-pass coolant.

Experimental Procedures

Four separate test exposures were conducted during this extended program; the materials included in each exposure are listed in Table I. Reference solutions provided direct evaluation of the candidate inhibitor mixtures within each test exposure. Total inhibitor concentration in each solution was 100 ppm, with the mixtures containing 50 ppm of each of the two chemicals except as indicated in the table. These concentrations were used to: 1) emphasize the differences in inhibiting characteristics of the different chemicals, 2) allow for depletion during exposure, and 3) provide a direct evaluation of inhibitors at a concentration applicable to cold static systems.

The solutions were prepared with filtered Columbia River water to simulate the natural environment of the Hanford cooling water systems. Typical analysis of the water is included in Appendix A. Stock solutions of each mixture were prepared at moderate dilution, and then an aliquot portion of each of the stock solutions was further diluted to 2000 ml of final solution in glass laboratory beakers for the tests. The test beakers with glass covers were set on shelves at eye level for ease of observation.

Metal specimens used for these tests were coupons cut from sheet material. The 1 in. square samples of aluminum alloys 1100 and 6061, and 1 1/2 in. round samples of ASTM A-212 carbon steel, were cleaned and weighed, and then suspended individually in the solutions. Five samples of each metal were exposed in each solution. Two additional carbon steel samples were suspended at the water line in some of the tests. Aluminum samples were prepared by etching for 1 min at 70 C in a solution of 10% (by weight) NaOH, followed by a 2 min rinse at room temperature in 10% (by volume) of concentrated (70% by weight) HNO₃. Carbon steel samples were prepared by cleaning in 15% (by volume) of concentrated (36% by weight) HCl inhibited with 1% (by volume) of formaldehyde solution (37%

HCHO by weight) to remove traces of mill scale, followed by light polishing with emery cloth and degreasing with acetone. The cleaned and weighed samples were suspended individually on plastic threads or plastic-coated wires, so that none of the samples would be subjected to galvanic corrosion by contact with dissimilar metals.

Selected samples of both carbon steel and aluminum were discharged from the tests at convenient intervals, and were cleaned, weighed, and examined. Aluminum samples were cleaned by immersion for 1 hr at 75 C in a mixture of 10% (by volume) of phosphoric acid (85% H_3PO_4), 20% (by weight) sodium dichromate, and 1% (by volume) glacial acetic acid, followed by rinsing, drying, and weighing. Carbon steel samples were cleaned in the 15% HCl-1% formaldehyde solution. All coupon surfaces were examined at 60 X, and the depth of all significant pits was measured by means of calibrated focusing.

The hydrogen ion concentration of each solution was measured just prior to insertion of the test samples, and was measured at intervals throughout the exposure period. These measurements were obtained by immersing the pH electrodes directly into the solutions in the beakers. The electrodes were rinsed with distilled water and wiped dry prior to each measurement. Measured pH values are shown in Appendix B. No attempt was made to adjust the pH of any of these mixtures.

RESULTS

Results from these screening tests include numerical data expressed as unit weights of metal removed from the samples, and include evaluation of type and severity of nonuniform corrosion. Since the corrosion which occurs on the metal surfaces in these static solutions is not distributed evenly over the entire surface, the corrosion is expressed as weight losses in mg/cm^2 .

The four test exposures were evaluated separately. Subtle differences in filtered water quality prevent quantitative comparison of results between the four exposures.

Aluminum

In these tests, hexavalent chromium, as sodium dichromate, was an effective corrosion inhibitor for aluminum. Four other materials: 1) sodium nitrite plus sodium silicate, 2) sodium sulfite plus sodium silicate, 3) sodium silicate alone, and 4) sodium hexametaphosphate, were also found to be effective inhibitors of aluminum corrosion during the 150 to 285 day exposures in these static tests. For initial 30 to 35 day exposure periods, some materials appeared better than sodium dichromate. Results from the four test exposures are shown in Figures 1, 2, 3, and 4. Weight losses and indications of pitting corrosion are shown in these figures for aluminum samples removed from the tests at various exposure times. A complete list of individual sample measurements is included in Appendix B.

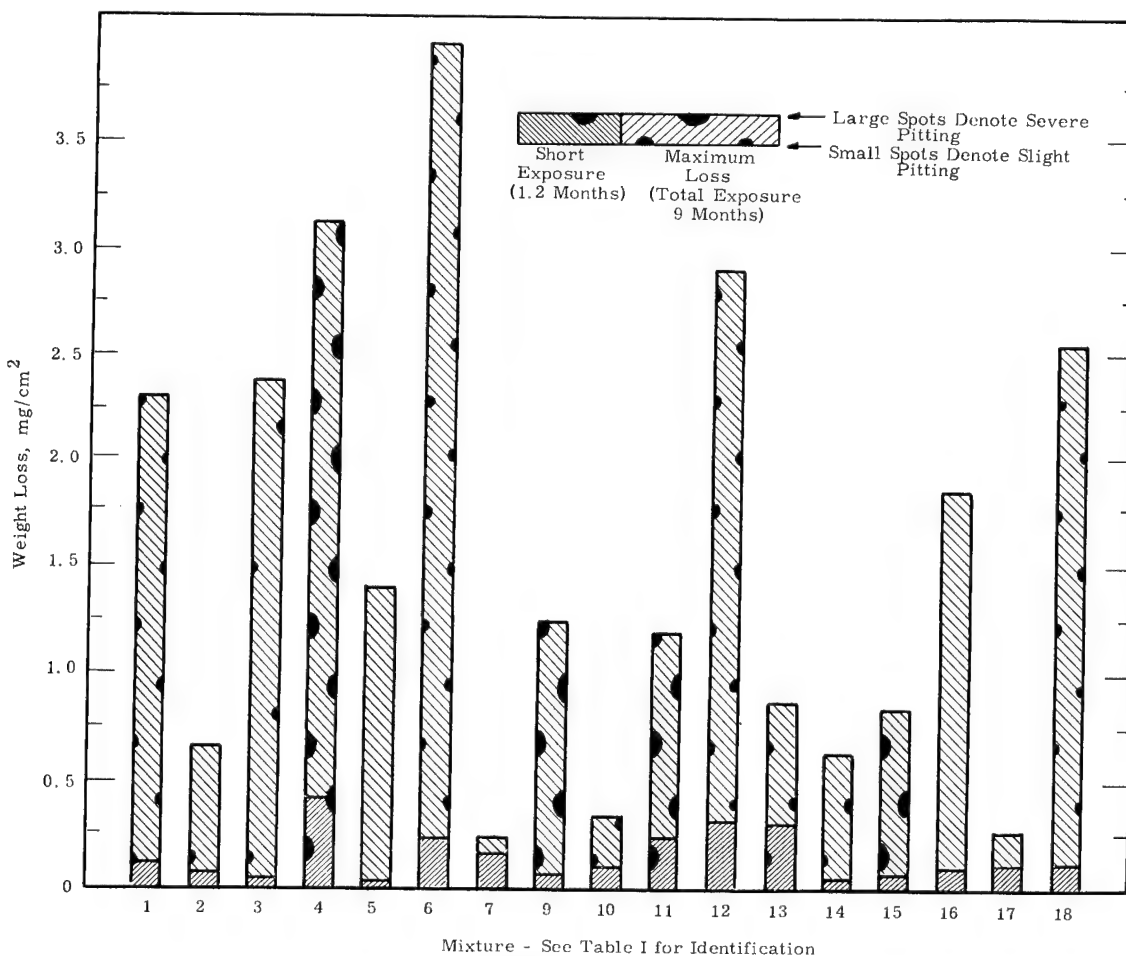


FIGURE 1
Aluminum Corrosion - Test Exposure A

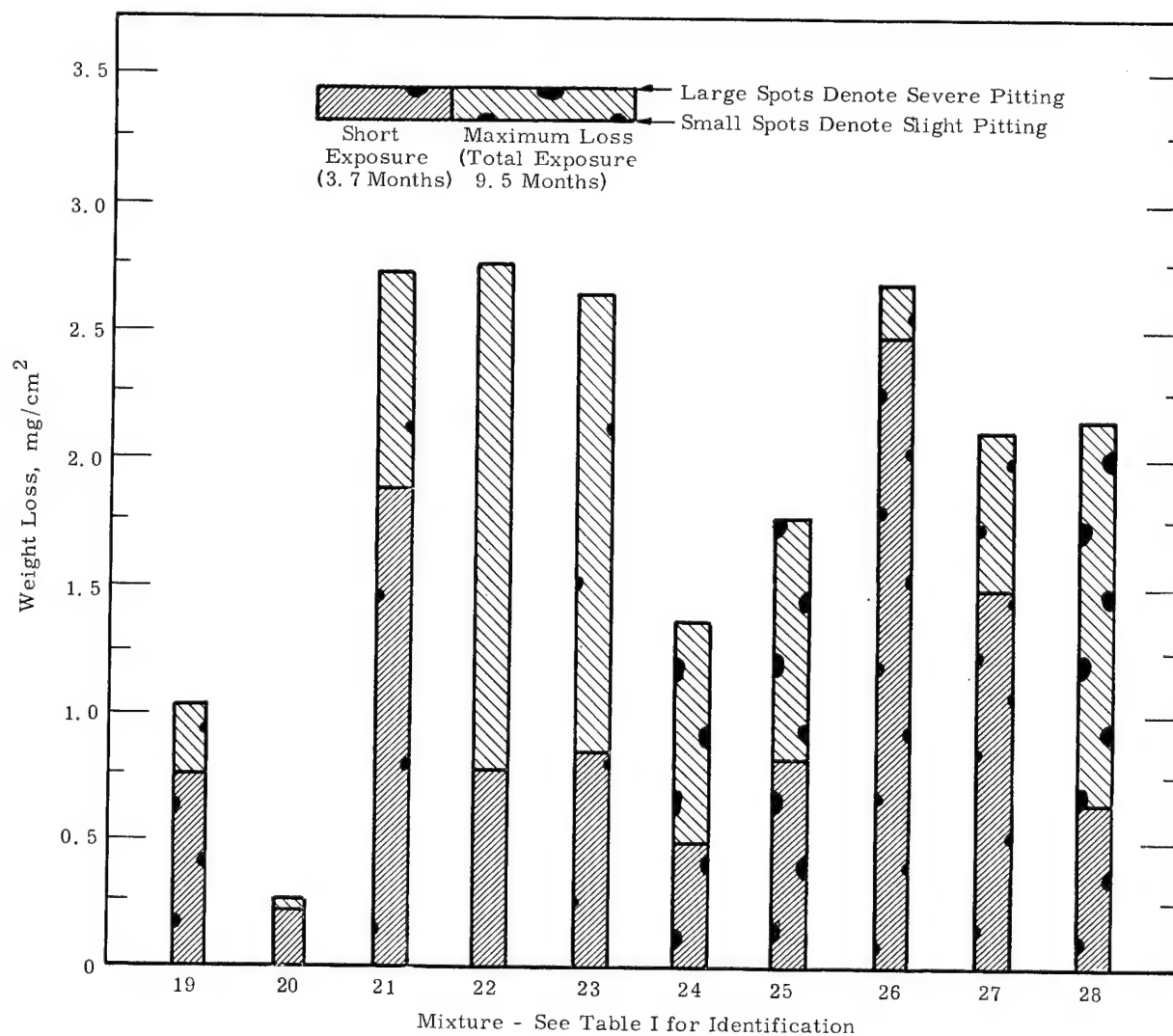


FIGURE 2
Aluminum Corrosion - Test Exposure B

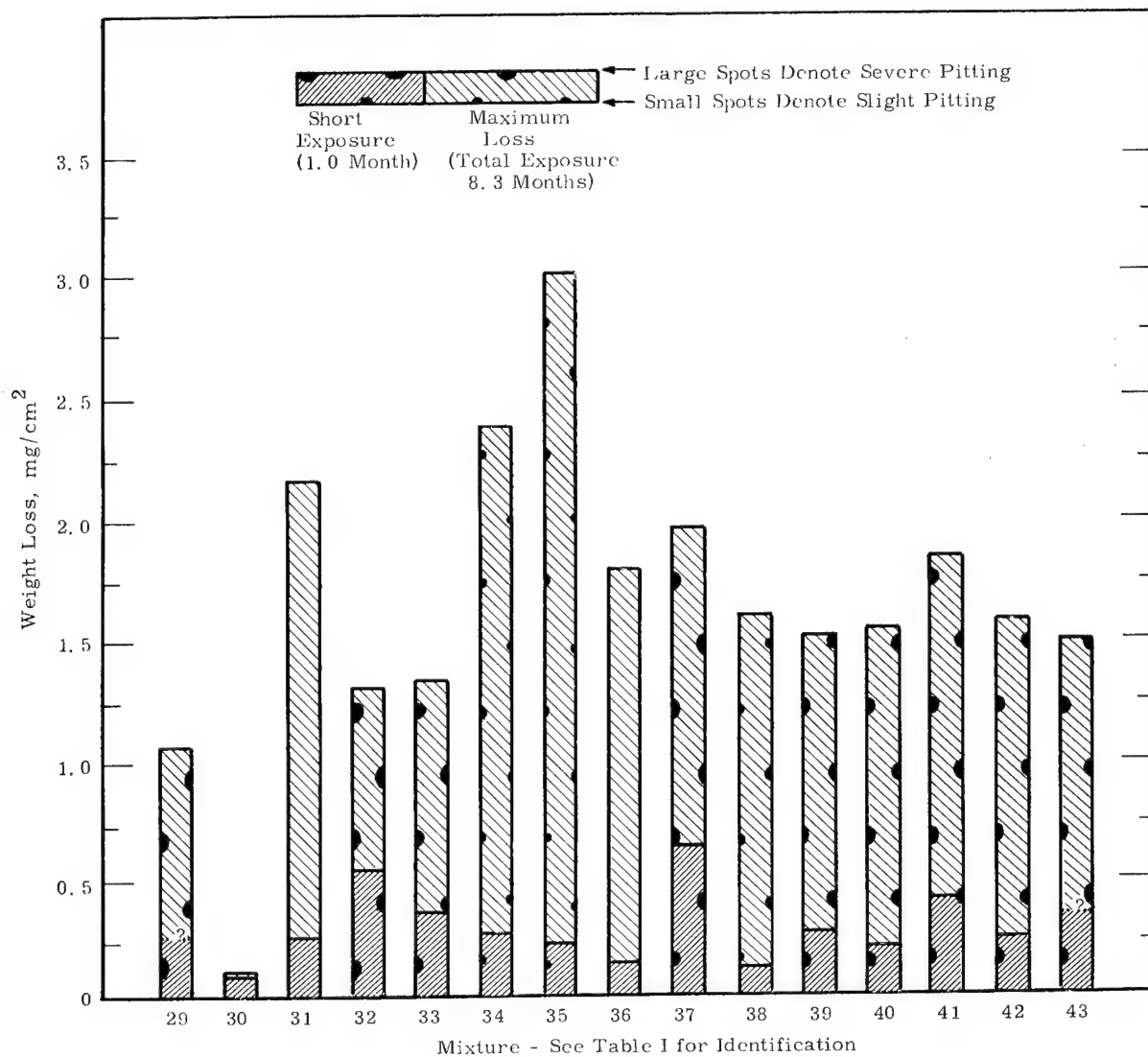


FIGURE 3
Aluminum Corrosion - Text Exposure C

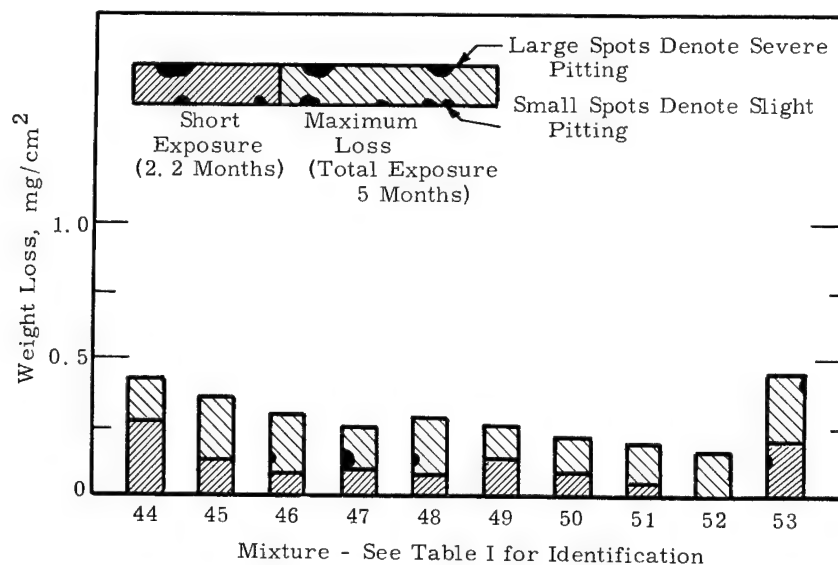


FIGURE 4
Aluminum Corrosion - Test Exposure.D

Weight losses at 35 days exposure, and maximum weight losses during the test, for Test Exposure A (total exposure = 270 days), are shown on the shaded bars of Figure 1. Sodium dichromate, known to be a good inhibitor of aluminum corrosion, was used as a reference solution in Test Exposure A. Aluminum weight losses after 35 days exposure in five other materials were equal to, or less than, the 0.07 mg/cm² weight loss measured in sodium dichromate.

These materials include sulfite-silicate Mixtures 5 and 15 (Figure 1), nitrite-silicate Mixtures 3 and 14, and proprietary filming Amine Material 9. Noticeable pitting occurred on samples in several of the solutions, including filming Amine Mixture 9, and sulfite - Na₂O:3.25 SiO₂ Mixture 15. Further evaluation of Test A mixtures over the full 270 day test period, using an arbitrary inhibiting indication of 0.7 mg/cm² loss (equivalent to 0.1 mill penetration of these aluminum samples), shows that three hexavalent chromium mixtures, sodium dichromate (2), chromium nitrate plus sodium dichromate (10), and sodium chrome glucosate (7), along with sodium hexametaphosphate (17), and the mixture of sodium nitrite plus Na₂O:3.25

SiO_2 (14), appeared to inhibit aluminum corrosion for the full 270 day period of the test.

Test Exposure B included several silicate mixtures and several other candidate inhibitors, and also included a reference exposure of filtered Columbia River water to provide an objective evaluation of the different test materials. Weight losses after 111 days and after the full 285 day test exposure are shown on Figure 2. Two materials showed some inhibitive properties during the first 111 days exposure. These two were sodium dichromate (20), and the mixture of sodium sulfite plus $\text{Na}_2\text{O}:2.5 \text{ SiO}_2$ (24). The latter mixture reduced total weight losses of the aluminum samples, but appeared to increase the tendency for the aluminum to suffer pitting attack. After full 285 day exposure, only sodium dichromate continued to show inhibitive properties for aluminum, while the other materials all showed tendencies toward increasing the corrosion of aluminum in varying degrees.

More information on promising inhibitor mixtures was obtained from a third test exposure, as shown in Figure 3. Weight of metal removed is shown on this figure for exposure periods of 30 and 250 days. The data for the 30 day exposure show that sodium dichromate (30), sodium nitrite plus $\text{Na}_2\text{O}:3.5 \text{ SiO}_2$ (38), and sodium nitrite plus $\text{Na}_2\text{O}:1.97 \text{ SiO}_2$ (36), provided about the same degree of inhibition of aluminum corrosion in these static, non-refreshed solutions. At longer exposure, sodium dichromate continued to protect the aluminum while the other mixtures caused increased corrosion and, in some cases, pitting of the aluminum.

Data from a fourth test exposure are shown in Figure 4, for exposure periods of 33 and 150 days, in solutions of the single chemicals; $\text{Na}_2\text{O}:3.2 \text{ SiO}_2$ (at different dosages), sodium dichromate, and sodium nitrite. Sodium dichromate further demonstrated superior inhibiting properties in this test; high concentrations of sodium silicate inhibited corrosion of the aluminum for the first 33 days of the test.

Steel

Chromium-containing mixtures, sodium nitrite mixtures, and a phosphate, were effective inhibitors of carbon steel corrosion in these static

tests. Sodium nitrite, sodium hexametaphosphate, and sodium dichromate, were about equal in effectiveness during initial 1 month exposure. The phosphate and dichromate continued to significantly inhibit carbon steel corrosion for full test exposures as long as 9 1/2 months. Numerical weight loss results, and pitting indications, from four test exposures are shown in Figures 5, 6, 7, and 8. Data from individual samples are in Appendix B.

Seven mixtures gave very low corrosion losses (less than 2.5 mg/cm^2) during initial 35 day exposure of Test A, as shown on Figure 5. These inhibiting mixtures were:

1. sodium hexametaphosphate (17),
2. sodium nitrite (1 and 18),
3. sodium nitrite plus $\text{Na}_2\text{O}:3.25 \text{ SiO}_2$ (4),
4. sodium dichromate (2),
5. sodium chrome glucosate (7),
6. sodium dichromate plus chromium nitrate (10), and
7. sodium dichromate plus $\text{Na}_2\text{O}:1.58 \text{ SiO}_2$ (13).

The phosphate material and three of the chromium-containing mixtures continued to show inhibition of carbon steel corrosion throughout the full test exposure of 270 days, with total losses of less than 2.5 mg/cm^2 . The sodium dichromate-sodium silicate mixture showed low total corrosion loss (7.1 mg/cm^2) but caused severe localized corrosion. The other mixtures of Test A permitted total corrosion greater than 26 mg/cm^2 .

Data from 111 and 285 day exposures in Test B (Figure 6) show that sodium dichromate and sodium nitrite provided corrosion inhibition up to 111 days, but that only sodium dichromate provided significant inhibition throughout the full test exposure. Carbon steel samples exposed at the surface of the solutions in Exposure B showed greater total weight loss than submerged samples in most of the solutions due to significant corrosion over larger areas of the sample surface (mostly near the water line) than occurred on submerged samples. Depth of penetration at the water line was about the same as on submerged coupon surfaces.

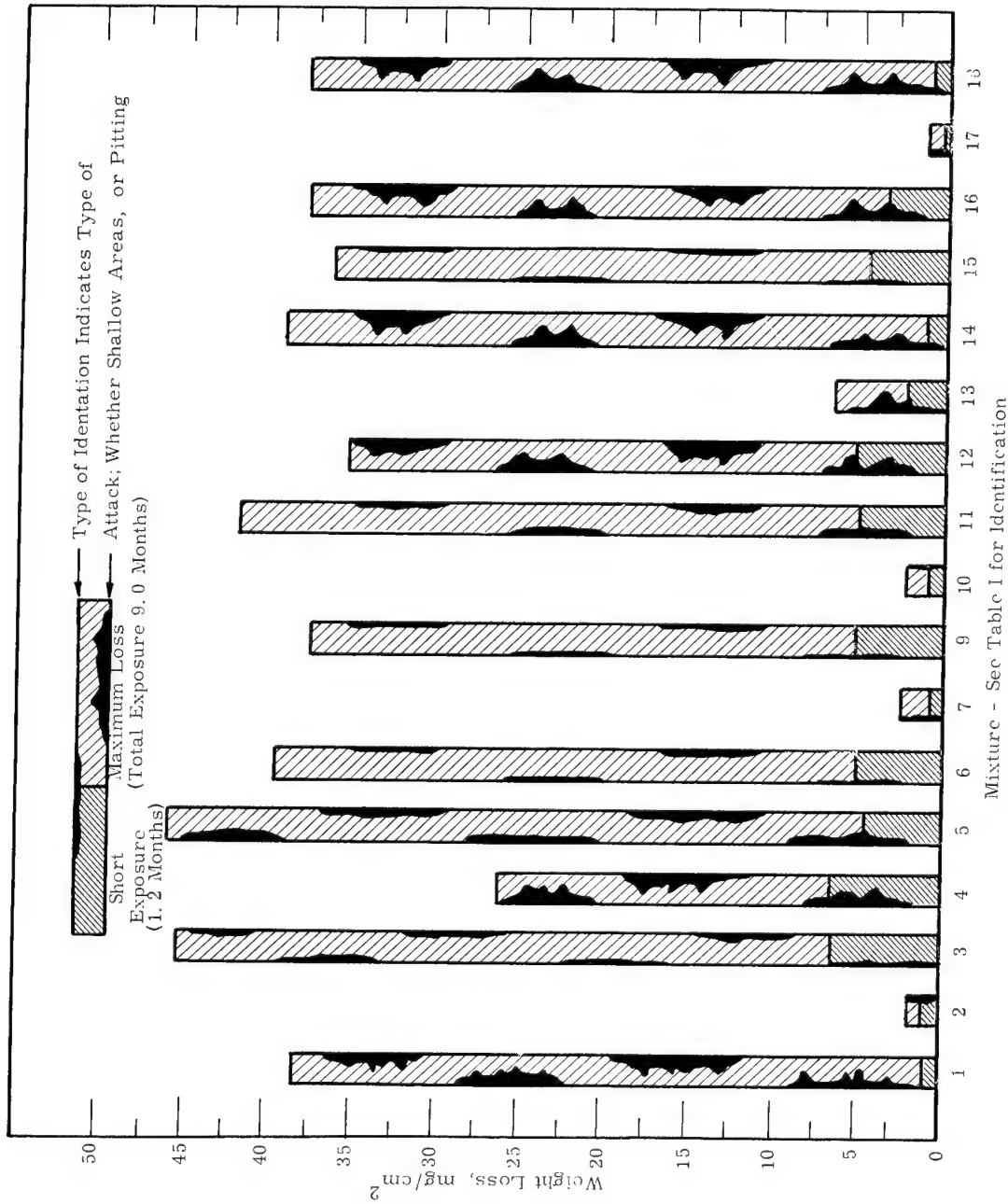


FIGURE 5
Carbon Steel Corrosion - Test Exposure A

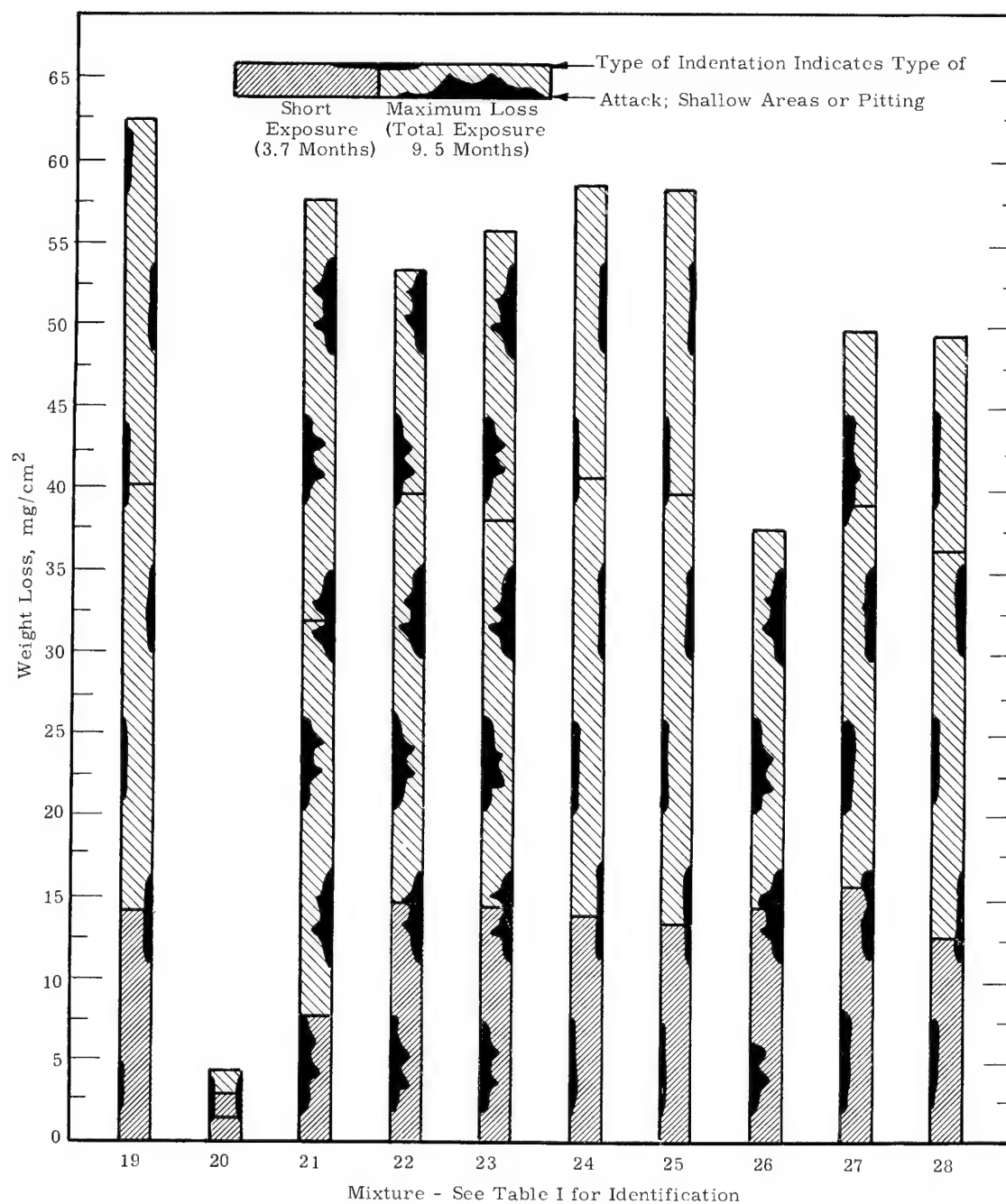


FIGURE 6
Carbon Steel Corrosion - Test Exposure B

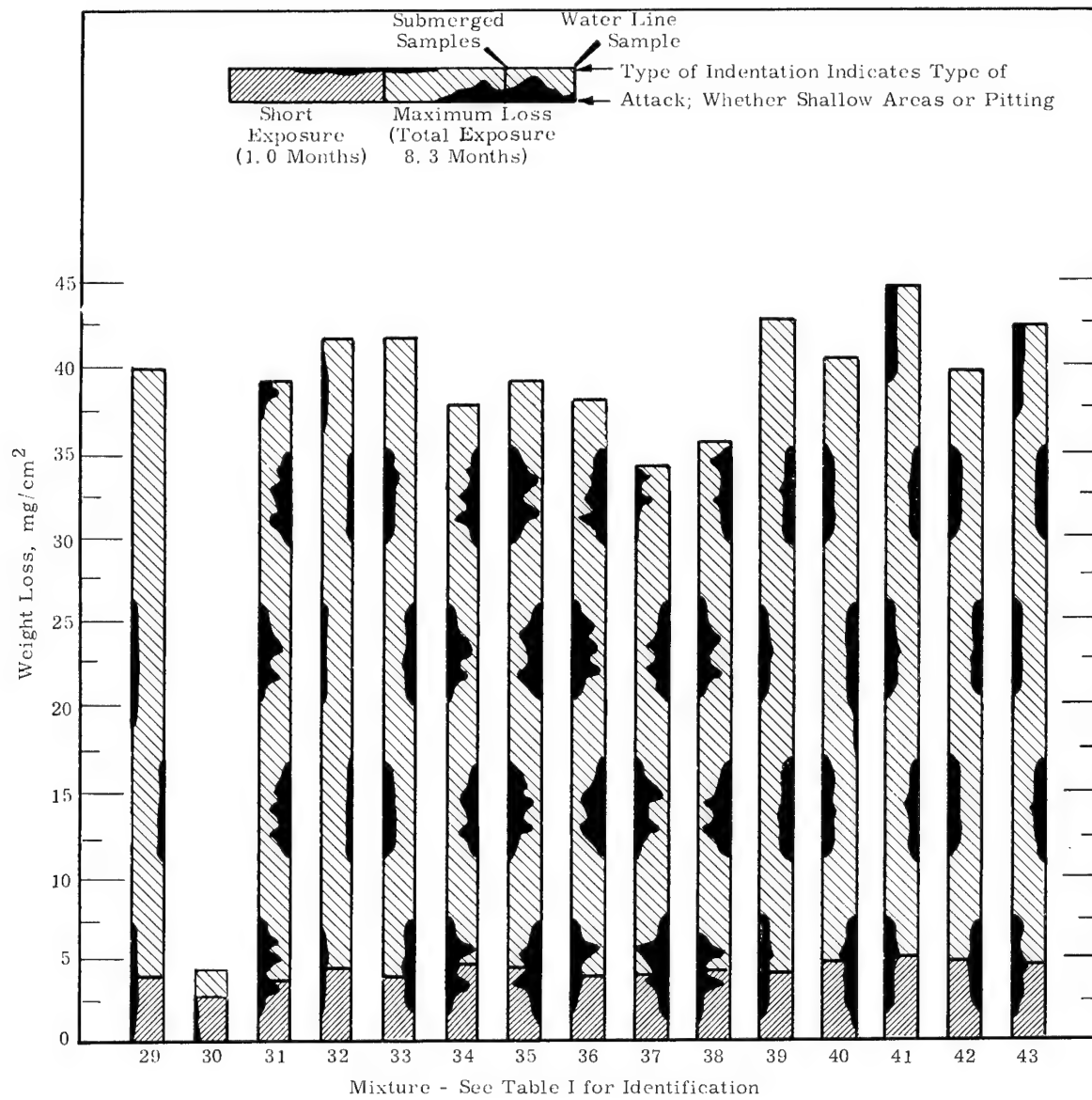


FIGURE 7
Carbon Steel Corrosion - Test Exposure C

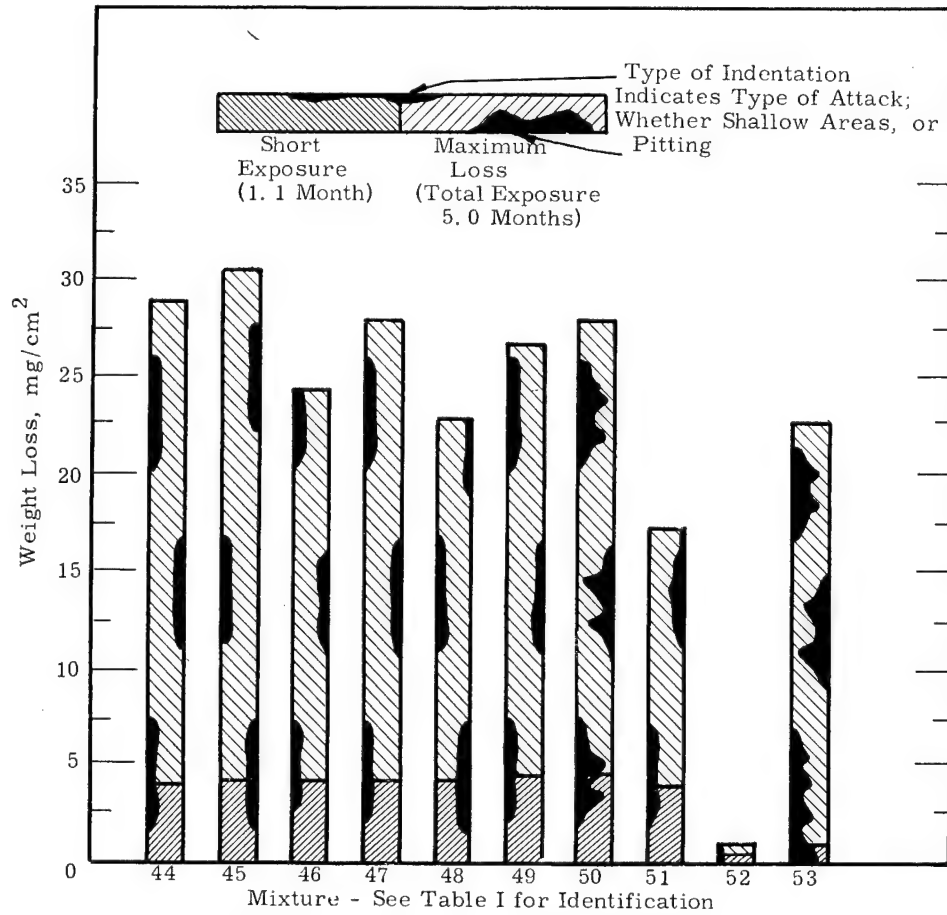


FIGURE 8
Carbon Steel Corrosion - Test Exposure D

Data from a third test exposure (Figure 7) show significant inhibition of carbon steel corrosion by sodium dichromate, but not by any other material, for exposure periods of either 30 or 250 days.

During a fourth test exposure (Figure 8), both sodium dichromate and sodium nitrite significantly inhibited carbon steel corrosion during an initial 33 day exposure, while sodium silicate solutions showed negligible inhibition. Only sodium dichromate continued to significantly inhibit corrosion during the full 150 days of the test. Samples in the sodium nitrite solution showed considerable pitting, but the depth of pits on long exposure samples (150 days) was about the same as on samples exposed for only 33 or 65 days.

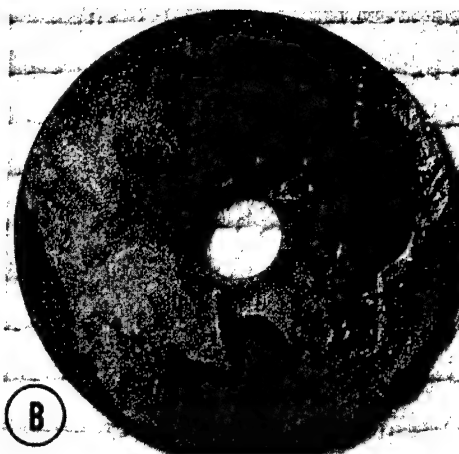
The corrosion which occurred on the steel samples was never completely uniform, but appeared to follow one of three patterns, as shown in Figure 9. One pattern consisted of corroded areas, with each area covering from one-tenth to one-half of the coupon face (Samples A and B in Figure 9). This pattern was typical of several of the systems, including the chromate, phosphate, and sulfite mixtures. As the areas grow in diameter, they begin to overlap one another, and these overlap regions appear to be the locations of maximum corrosion penetration. A different corrosion pattern was visible on samples in the nitrite mixtures, as illustrated by Samples C and D in Figure 9. This pattern consisted initially of many small pits. The appearance of long-exposure samples indicates that these pits grow to a certain diameter and depth, and then stop. Larger corroding areas eventually overtake and obliterate the small pits (Sample D). A third pattern of deeply corroded areas occurred on the samples exposed to a mixture of sodium dichromate and sodium silicate (Sample E of Figure 9). These areas covered only small portions of the sample surfaces, but apparently continued to increase in depth as exposure continued.

Depletion

During these static tests, sodium dichromate and sodium nitrite were only slightly depleted from the solutions, but considerable depletion of silicate solutions occurred. Measurements on selected solutions after 3 months exposure showed: (1) more than 75% of original sodium dichromate still in



(A)



(B)

Overlapping Corrosion Areas, After Short and Long Exposure

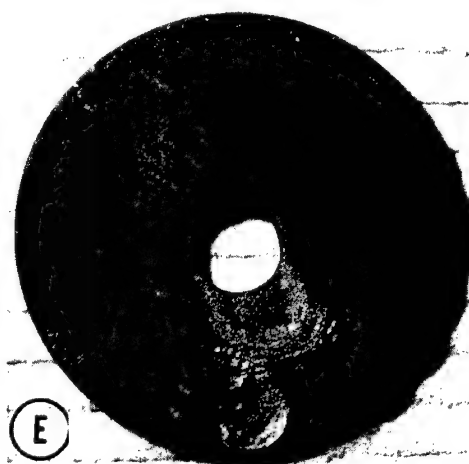


(C)



(D)

Small Pits and Corroding Areas, After Short and Long Exposure



(E)

Deeply Corroded
Areas After Long
Exposure

FIGURE 9

Corrosion Patterns on Carbon Steel Samples

solution, (2) nearly 50% of sodium nitrite remained, while (3) only 3 to 9% of sodium silicate remained in different solutions. It should be noted that a sodium silicate precipitate is visibly adsorbed onto the surfaces of solution containers, and onto coupon surfaces, from static solutions. These results did not define the effects of depletion on corrosion inhibition by these materials.

Application to Large-Scale Systems

Static Systems

Most water supply systems include portions in which water is held nearly static for long periods of time. These static systems include storage tanks, piping dead-legs, and cross-tie lines connecting one water system with another. Relatively large dosages of inhibitors are usually added to static systems to overcome loss of inhibitor from decomposition, precipitation of the inhibitor out of solution, or from slow flow or leakage of inhibited water out of the system.

Carbon steel corrosion in static ambient-temperature systems using treated Columbia River water may be effectively inhibited for as long as 9 months by the addition of 100 ppm, or more, of sodium dichromate or sodium hexametaphosphate. Other chromium-containing mixtures are also effective. Sodium nitrite (or a mixture of sodium nitrite plus sodium silicate) is effective for periods of several days without refreshment, and partially protects carbon steel from uniform corrosion for a month or more, but some pitting corrosion may occur.

Corrosion of 1100 and 6061 aluminum alloys in static ambient-temperature systems using treated Columbia River water may also be inhibited for as long as 9 months by the addition of 100 ppm, or more, of sodium dichromate or sodium hexametaphosphate. Other materials, specifically $\text{Na}_2\text{O}:3.2 \text{ SiO}_2$ and mixtures of $\text{Na}_2\text{O}:3.2 \text{ SiO}_2$ or $\text{Na}_2\text{O}:3.5 \text{ SiO}_2$ with either sodium nitrite or sodium sulfite, also reduce aluminum metal loss, in many cases for periods of 1 to 3 months, but do not provide protection in nonrefreshed systems for longer periods of time, and, in some cases, may permit pitting corrosion of the aluminum to occur.

Dynamic Systems Containing Aluminum and Carbon Steel

Most of the Hanford reactors are cooled with single-pass flow of treated Columbia River water through aluminum and steel piping. Only a few parts per million of an inhibitor can be added continuously to single-pass cooling water because of chemical cost, and inhibitor effectiveness at low concentrations may be much reduced from that at 100 ppm. However, in dynamic, single-pass systems, the inhibitor concentration near the metal surface would be continually maintained by chemical addition to the water, and this continuous refreshment may overcome the effects of low concentration.

Chromium-containing mixtures, sodium hexametaphosphate, and some mixtures of sodium nitrite with sodium silicate appear to be effective corrosion inhibitors in systems containing both aluminum and steel. For the steel and aluminum cooling systems of the Hanford reactors, where inhibition of aluminum corrosion is of prime importance, mixtures of sodium nitrite with sodium silicate are possible candidates to replace sodium dichromate. These mixtures should be tested under dynamic conditions prototypic of reactor operation, with continuous inhibitor addition at the low concentrations required for the single-pass cooling system, before they are used in full-scale systems.

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APPENDIX A

TYPICAL ANALYSIS OF FILTERED WATER

Treated River Water

<u>Constituent</u>	<u>Average Concentration, ppm</u>
Total Solids	90
Turbidity	0.005
Iron	0.01
Sulfate (SO_4)	20
Chloride	1.5
Hardness (as CaCO_3)	70
Calcium	21
Magnesium	5.2
Alkalinites (as CaCO_3)	
Methyl Orange	55
Phenolphthalein	0.0
Free CO_2	0.5
Silica (as SiO_2)	6.0
Sodium	6
pH	6.6

APPENDIX
DATA TABLE

TEST EXPOSURE, A

Aluminum and Carbon Steel,
Weight Loss (mg) Maximum Pit Depth (mm)

Exposure Months: Inhibitor Mixture ^(a)	Aluminum								Carbon Steel				
	1. 2		2. 3		5		9		1. 2		2. 3		5
	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm	mg
1	1.6	0	8.9	0	34.3	0.1	32.8	0	20	0.10	92	0.08	387
							33.3	0					
2	1.0	0	1.3	0	0.6	0	10.0	0.06	26	0.02	25	0.05	30
							0.6	0					
3	0.6	0	4.5	0	21.5	0	35.7	0.06	144	0.05	224	0.02	528
							35.2	0					
4	6.3	0	10.9	<0.02	36.3	0	46.8 ^(b)	0	145	0.10	237	0.05	497
							35.5 ^(b)	0.05	5.5 mo				
5	0.1	0	3.6	0	12.6	0	11.6	0	98	0.02	166	0.02	448
							20.7	0					
6	3.2	0	7.6	0	35.8	0	59.8	0.24	110	0.02	189	<0.02	370
							38.2	0					
7	2.3	0	1.6	0	3.4	0	1.7	0	26	0.01	39	0.05	46
							1.6	0					
9	0.9	0.08	3.4	0	17.1	0	18.2	0.08	114	0.01	222	0.05	440
							18.4	0.10					
10	1.4	0.05	1.3	0	3.2	0.05	5.0	0	26	0.02	32	0.02	32
							0.3	0					
11	3.3	0.13	4.2	0.13	10.4	0.36	17.6	0.15	116	0.01	203	0.02	454
							15.3	0.05					
12	4.6	0	6.8	<0.02	35.1	0	43.4	0.06	117	0.15	238	0.08	520
							39.2	0.08					
13	4.5	0	1.2	0.05	2.6	0.02	2.3	0.05	47	0.05	57	0.25	112
							10.8	0.02					
14	0.7	0	2.7	0	9.2	0.05	9.2	0	33	0.20	183	0.05	493
							8.4	0					
15	1.0	0	3.1	0.08	6.8	0	12.4	0.40	104	0.02	214	0.02	428
							8.9	0.28					
16	1.4	0	3.8	0	16.0	0	25.3	0	81	0.08	216	0.02	469
							27.3	0					
17	1.6	0	1.7	0	4.0	0.25	2.9	0	9	0.02	15	0.05	17
							3.8	0					
18	1.7	0.08	4.9	0	38.1	0	30.4	0	24	0.13	128	0.08	390
							28.8	0					

(a) See Table I, page 4, for Identification

(b) Final samples discharged from Solution #4 After 5.5 months exposure.

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APPENDIX B
DATA TABULATION

TEST EXPOSURE, A
Aluminum and Carbon Steel,
Weight Loss (mg) Maximum Pit Depth (mm)

			Carbon Steel								pH		
5	9		1. 2		2. 3		5		9		0. 0	2. 3	5
mm	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm			
0. 1	32. 8	0	20	0. 10	92	0. 08	387	0. 25	826	0. 28	8. 7	8. 4	8. 5
	33. 3	0							813	0. 24			
0	10. 0	0. 06	26	0. 02	25	0. 05	30	0. 08	39	0. 04	10. 1	7. 9	8. 3
	0. 6	0							39	0. 06			
0	35. 7	0. 06	144	0. 05	224	0. 02	528	0. 12	972	0. 16	10. 0	8. 4	8. 8
	35. 2	0							975	0. 12			
0	46. 8 ^(b)	0	145	0. 10	237	0. 05	497	0. 10	545 ^(b)	0. 09	8. 8	8. 0	8. 1
	35. 5 ^(b)	0. 05							564 ^(b)	0. 11			
0	11. 6	0	98	0. 02	166	0. 02	448	0. 07	988	0. 10	9. 9	8. 1	8. 6
	20. 7	0							945	0. 06			
0	59. 8	0. 24	110	0. 02	189	<0. 02	370	0. 03	855	0. 06	9. 9	7. 8	8. 4
	38. 2	0							733	0. 09			
0	1. 7	0	26	0. 01	39	0. 05	46	0. 04	46	0. 10	9. 7	8. 0	8. 3
	1. 6	0							54	0. 13			
0	18. 2	0. 08	114	0. 01	222	0. 05	440	0. 02	818	0. 10	8. 2	7. 6	7. 7
	18. 4	0. 10							785	0. 07			
0. 05	5. 0	0	26	0. 02	32	0. 02	32	0. 04	35	0. 01	9. 2	7. 9	8. 2
	0. 3	0							50	0. 04			
0. 36	17. 6	0. 15	116	0. 01	203	0. 02	454	0. 06	902	0. 14	7. 5	7. 6	7. 6
	15. 3	0. 05							778	0. 04			
0	43. 4	0. 06	117	0. 15	238	0. 08	520	0. 08	765	0. 13	8. 2	8. 1	8. 2
	39. 2	0. 08							727	0. 15			
0. 02	2. 3	0. 05	47	0. 05	57	0. 25	112	0. 35	152	0. 35	9. 5	8. 6	8. 8
	10. 8	0. 02							151	0. 40			
0. 05	9. 2	0	33	0. 20	183	0. 05	493	0. 30	830	0. 12	7. 4	8. 4	8. 3
	8. 4	0							848	0. 25			
0	12. 4	0. 40	104	0. 02	214	0. 02	428	0. 06	790	0. 06	7. 7	7. 6	7. 7
	8. 9	0. 28							764	0. 09			
0	25. 3	0	81	0. 08	216	0. 02	469	0. 08	818	0. 10	9. 8	8. 5	8. 7
	27. 3	0							823	0. 08			
0. 25	2. 9	0	9	0. 02	15	0. 05	17	0. 17	22	0. 20	6. 9	8. 0	8. 4
	3. 8	0							29	0. 10			
0	30. 4	0	24	0. 13	128	0. 08	390	0. 25	838	0. 33	6. 7	8. 4	8. 4
	28. 8	0							815	0. 26			

4 After 5. 5 months exposure.

(2)

TEST EXPOSURE, B

Exposure Months:	Aluminum						Carbon Steel					
	3.7		7.6		9.5		3.7		7.6		9.5	
	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm
Inhibitor Mixture ^(a)												
19	11.5	0.30	14.3	0	21.3	0	306	0.05	587	0.05	742	0.10
					26.5	0					868	0.07
					23.3	0						
20	3.6	0	2.0	0	4.0	0	62	0.05	92	0.05	30	0.05
					3.5	0					51	0.05
					2.0	0						
21	28.1	0	29.9	0	40.6	0	163	0.20	457	0.25	628	0.28
					36.3	0					690	0.25
					32.9	0.10						
22	11.8	0	15.0	0	30.2	0	318	0.20	655	0.15	859	0.15
					32.6	0					829	0.15
					41.3	0						
23	12.7	0.02	15.2	0	40.1	0	308	0.05	685	0.15	817	0.15
					38.8	0					824	0.10
					36.6	0						
24	7.8	0.10	15.2	0.15	20.2	0.35	299	0.03	652	0.05	800	0.05
					13.3	0.20					879	0.05
					18.6	0.10						
25	12.2	0.15	7.9	0.15	26.4	0.15	289	0.05	665	0.03	786	0.05
					22.4	0.10					857	0.05
					18.6	0.15						
26	37.3	0.05	34.4	0.10	37.9	0	315	0.15	638	0.15	811	0.15
					35.3	0					781	0.18
					40.2	0						
27	22.4	0	20.2	0.10	31.9	0	339	0.05	795	0.05	840	0.05
					23.6	0.10					840	0.10
					27.5	0						
28	9.9	0.15	19.3	0.15	7.2	0.15	271	0.05	609	0.05	706	0.05
					16.8	0					781	0.05
					11.9	0.05						

(a) See Table I, page 4, for Identification

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TEST EXPOSURE, B

.5	Carbon Steel								pH				
	3.7				7.6				1				
	9.5				Water Line				Day				
mm	mg	mm	mg	mm	mg	mm	mg	mm	0.0	Day	3.7	7.6	9.5
0	306	0.05	587	0.05	742	0.10	1357	0.10	8.2	7.8	7.6	5.6	6.5
0					868	0.07	1283	0.10					
0													
0	62	0.05	92	0.05	30	0.05	52	0.10	7.4	8.8	9.4	8.4	7.5
0					51	0.05	42	0.10					
0													
0	163	0.20	457	0.25	628	0.28	1066	0.20	8.2	7.8	9.6	8.0	7.5
0					690	0.25	1243	0.20					
0.10													
0	318	0.20	655	0.15	859	0.15	1142	0.18	8.6	8.3	9.1	7.7	7.5
0					829	0.15	1154	0.15					
0													
0	308	0.05	685	0.15	817	0.15	1152	0.10	8.6	8.4	9.2	7.8	7.6
0					824	0.10	1201	0.15					
0													
0.35	299	0.03	652	0.05	800	0.05	1161	0.10	8.8	8.4	8.8	7.0	6.8
0.20					879	0.05	1265	0.10					
0.10													
0.15	289	0.05	665	0.03	786	0.05	1191	0.10	9.0	8.4	8.8	7.2	7.4
0.10					857	0.05	1252	0.10					
0.15													
0	315	0.15	638	0.15	811	0.15	367	0.10	8.0	7.6	9.4	8.0	7.3
0					781	0.18	322	0.20					
0													
0	339	0.05	795	0.05	840	0.05	947	0.20	8.7	8.3	8.9	7.0	6.9
0.10					840	0.10	1077	0.15					
0													
0.15	271	0.05	609	0.05	706	0.05	1046	0.15	6.8	7.0	7.5	5.4	6.0
0					781	0.05	1063	0.10					
0.05													

2

TEST EXPOSURE, C

Exposure Months:		Aluminum													
		1.0		4.8		6.3		7.4		8.3		1.0		4.8	
Inhibitor	Mixture	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm	mg	mm
29	~4	0.30		14.0	0	15.2	0.30	14.4	0	15.9	0.25	87	0.01	459	0.07
30	1.5	0		1.4	0	0.5	0	0.8	0	1.2	0	25	0.03	31	0.02
31	3.7	0		32.6	0	28.2	0	32.3	0	29.4	0	80	0.15	422	0.10
32	8.3	0.70		12.5	0.25	14.6	0.30	14.7	0.43	19.4	0.50	98	0.01	546	0.03
33	5.4	0.20		13.9	0	18.5	0.30	20.1	0	19.4	0.30	84	0.01	433	0.03
34	4.2	0		21.7	0.08	33.5	0	31.6	0.10	35.7	0	115	0.02	437	0.02
35	3.3	0.01		19.3	0.07	32.9	0.02	37.9	0.07	44.8	0.06	93	0.15	430	0.10
36	2.1	0.01		17.2	0	20.5	0	23.9	0	27.1	0	82	0.07	417	0.15
37	9.6	0.15		14.1	0.03	27.0	0.40	29.6	0.07	28.4	0	83	0.15	422	0.15
38	1.7	0.02		11.9	0	16.8	0.02	19.0	0.06	23.9	0.07	94	0.15	417	0.15
39	3.9	0		18.3	0.02	19.2	0.40	22.7	0.48	16.3	0.40	85	0.02	449	0.03
40	3.2	0.60		15.2	0.30	20.9	0.40	20.3	0.08	23.0	0.50	109	0.01	442	0.02
41	6.3	0.50		13.2	0.05	21.7	0.40	20.1	0	27.5	0.90	110	0.01	449	0.02
42	3.5	0.30		11.5	0.20	23.3	0.45	17.5	0	22.8	0.40	105	0.01	472	0.05
43	~5	0.28		14.0	0.10	19.3	0.25	15.8	0.22	23.2	0.35	102	0.01	487	0.03

TEST EXPOSURE, D

Exposure Months:		2.2		3		4		5		1.1		2.2		3	
44	4.0	0		4.6	0	--	0	6.2	0	89	0.03	202	<0.01	279	0.06
45	1.9	0		2.8	0	5.3	0	3.3	0	93	<0.01	188	<0.01	254	0.01
46	1.7	0		2.1	0	4.3	0.02	3.4	0	91	<0.01	173	0.02	240	0.08
47	1.6	0.16		2.3	0.07	3.8	0.06	3.1	0	94	<0.01	185	<0.01	254	0.01
48	1.3	0.04		2.8	0.05	4.1	0	3.0	0	95	<0.01	192	<0.01	273	0.07
49	1.9	0		2.2	0	3.9	0	2.6	0	105	<0.01	230	0.01	289	0.01
50	1.0	0		3.4	0	2.8	0	2.6	0	109	0.05	196	0.04	286	0.10
51	1.0	0		3.0	0	2.4	0.08	0.8	0	89	<0.01	176	0.09	267	0.07
52	0.0	0		2.4	0	1.2	0	0.4	0	10	0.07	12	0.05	8	0.07
53	3.3	0.12		5.1	0	6.8	0	6.5	0	21	0.20	46	0.21	71	0.26

(a) See Table I, page 4, for Identification

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TEST EXPOSURE, C

Carbon Steel										pH					
1.0		4.8		6.3		7.4		8.3		0.0	1.0	4.8	6.3	7.4	8.3
ng	mm	mg	mm	mg	mm	mg	mm	mg	mm						
7	0.01	459	0.07	698	0.07	788	0.12	868	0.10	8.1	7.8	6.5	7.1	6.9	6.8
5	0.03	31	0.02	65	0.10	64	0.07	69	0.08	7.6	8.2	7.5	7.8	8.2	8.5
0	0.15	422	0.10	565	0.13	665	0.	850	0.10	7.9	8.7	8.2	7.9	8.2	8.2
8	0.01	546	0.03	653	0.06	772	0.08	893	0.08	8.0	7.4	7.0	7.2	7.5	7.9
4	0.01	433	0.03	536	0.08	764	0.08	903	0.13	8.2	7.8	7.7	7.4	7.2	8.1
5	0.02	437	0.02	659	0.07	757	0.09	829	0.10	8.4	8.6	8.1	7.8	8.0	8.2
3	0.15	430	0.10	566	0.11	684	0.10	847	0.06	7.9	8.6	7.5	7.5	8.1	8.2
2	0.07	417	0.15	562	0.20	701	0.22	834	0.10	8.8	8.8	8.2	7.9	7.7	8.2
3	0.15	422	0.15	591	0.16	662	0.19	746	0.12	7.8	8.8	7.3	7.7	7.9	8.0
4	0.15	417	0.15	559	0.13	687	0.20	771	0.17	7.9	8.8	7.8	7.8	8.0	8.2
5	0.02	449	0.03	614	0.08	769	0.10	924	0.08	8.4	8.1	8.0	7.6	7.6	8.2
9	0.01	442	0.02	657	0.10	788	0.10	879	0.11	8.5	7.8	7.9	7.7	7.8	8.1
0	0.01	449	0.02	654	0.12	816	0.20	961	0.14	8.2	7.6	7.8	7.9	8.0	8.2
5	0.01	472	0.05	664	0.07	827	0.15	860	0.12	7.6	7.8	7.3	7.7	7.9	7.9
2	0.01	487	0.03	676	0.10	838	0.14	917	0.12	7.5	7.6	7.4	6.8	7.6	8.0

TEST EXPOSURE, D

<u>2. 2</u>		<u>3</u>		<u>4</u>		<u>5</u>		<u>Water Line</u>		<u>0. 0</u>	<u>1. 1</u>	<u>2. 2</u>	<u>3</u>	<u>New</u> <u>3 Sol.</u>	<u>4</u>	<u>New</u> <u>4 Sol.</u>	<u>5</u>
202	<0.01	279	0.06	375	0.07	513	0.05	628	0.10	6.5	7.4	7.4	7.6	7.3	7.0	7.5	7.2
88	<0.01	254	0.01	358	0.02	504	0.05	662	0.10	7.0	7.4	7.3	7.8	7.8	7.4	7.0	7.3
73	0.02	240	0.08	348	0.02	488	0.08	531	0.10	7.2	7.7	7.5	7.8	7.6	7.4	7.0	7.5
185	<0.01	254	0.01	360	0.02	467	0.05	609	0.12	7.2	7.8	7.2	7.7	8.2	7.4	6.7	7.6
192	<0.01	273	0.07	358	0.03	493	0.03	492	0.08	7.3	7.9	7.3	7.9	8.7	7.4	6.6	7.4
230	0.01	289	0.01	401	0.05	506	0.06	576	0.05	8.7	7.6	7.4	7.9	9.3	8.2	7.3	7.6
196	0.04	286	0.10	379	0.10	514	0.04	604	0.09	8.6	7.4	7.7	8.3	9.6	8.5	9.0	8.0
176	0.09	267	0.07	322	0.07	376	0.08	312	0.09	9.6	8.3	8.1	8.6	9.8	8.2	9.4	8.5
12	0.05	8	0.07	14	0.03	15	0	24	0.03	6.3	7.6	7.6	8.1	6.7	7.4	6.3	7.1
46	0.21	71	0.26	72	0.25	--	0	496	0.30	6.5	7.8	7.8	8.6	7.7	7.8	6.4	7.7

2

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1	AEC SCIENTIFIC REPRESENTATIVE, JAPAN	1	IIT RESEARCH INSTITUTE
3	ATOMIC ENERGY COMMISSION, WASHINGTON	1	INTERNATIONAL BUSINESS MACHINES CORPORATION
4	ATOMIC ENERGY OF CANADA LIMITED	2	IOWA STATE UNIVERSITY
		2	JET PROPULSION LABORATORY
2	ATOMIC ENERGY OF CANADA LIMITED, WHITESHELL	1	JOHNS HOPKINS UNIVERSITY
4	ATOMICS INTERNATIONAL	3	KNOLLS ATOMIC POWER LABORATORY
1	AVCO CORPORATION	1	LING TEMCO VOUGHT, INC.
4	BABCOCK AND WILCOX COMPANY	1	LOCKHEED-GEORGIA COMPANY
2	BATTELLE MEMORIAL INSTITUTE	1	LOCKHEED MISSILES AND SPACE COMPANY (NASA)
6	*BATTELLE-NORTHWEST	3	LOS ALAMOS SCIENTIFIC LABORATORY
2	BEERS (ROLAND F.), INC.	1	M & C NUCLEAR, INC.
1	BERYLLIUM CORPORATION	1	MALLINCKRODT CHEMICAL WORKS
1	BLUME (JOHN A.) AND ASSOCIATES	1	MARE ISLAND NAVAL SHIPYARD
2	BROOKHAVEN NATIONAL LABORATORY	1	MARITIME ADMINISTRATION
1	BUREAU OF MINES, ALBANY	1	MARTIN-MARIETTA CORPORATION
		1	MINNESOTA MINING AND MANUFACTURING COMPANY (BRANDT)

Ptd.	Standard Distribution	Ptd.	Standard Distribution
1	MOUND LABORATORY	1	SAN FRANCISCO OPERATIONS OFFICE
		2	SANDIA CORPORATION, ALBUQUERQUE
1	NASA LEWIS RESEARCH CENTER	1	SANDIA CORPORATION, LIVERMORE
		1	SOUTHWEST RESEARCH INSTITUTE
1	NASA MANNED SPACECRAFT CENTER	1	STANFORD UNIVERSITY (SLAC)
2	NASA SCIENTIFIC AND TECHNICAL INFORMATION FACILITY	1	SYLVANIA ELECTRIC PRODUCTS, INC.
		1	TENNESSEE VALLEY AUTHORITY
2	NATIONAL BUREAU OF STANDARDS	1	TRW SPACE TECHNOLOGY LABORATORIES (NASA)
1	NATIONAL BUREAU OF STANDARDS (LIBRARY)	1	UNION CARBIDE CORPORATION, CLEVELAND
2	NATIONAL LEAD COMPANY OF OHIO	2	UNION CARBIDE CORPORATION (ORGDP)
4	*NATIONAL REACTOR TESTING STATION (PPCO)	5	UNION CARBIDE CORPORATION (ORNL)
1	NAVAL POSTGRADUATE SCHOOL		
3	NAVAL RESEARCH LABORATORY	1	UNION CARBIDE CORPORATION (PADUCAH PLANT)
		2	UNITED NUCLEAR CORPORATION (NDA)
1	NRA, INC.	1	U. S. GEOLOGICAL SURVEY, DENVER
1	NUCLEAR MATERIALS AND EQUIPMENT CORPORATION	1	U. S. GEOLOGICAL SURVEY, MENLO PARK
1	NUCLEAR METALS, INC.	1	U. S. GEOLOGICAL SURVEY, WASHINGTON
1	NUCLEAR UTILITY SERVICES, INC.	1	U. S. PATENT OFFICE
1	OFFICE OF ASSISTANT GENERAL COUNSEL FOR PATENTS (AEC)	2	UNIVERSITY OF CALIFORNIA, BERKELEY
2	OFFICE OF NAVAL RESEARCH	2	UNIVERSITY OF CALIFORNIA, LIVERMORE
1	OFFICE OF NAVAL RESEARCH (CODE 422)	1	UNIVERSITY OF PUERTO RICO
1	OHIO STATE UNIVERSITY	1	WESTERN RESERVE UNIVERSITY (MAJOR)
1	PETROLEUM CONSULTANTS	4	WESTINGHOUSE BETTIS ATOMIC POWER LABORATORY
1	PHYSICS INTERNATIONAL, INC.	1	WESTINGHOUSE ELECTRIC CORPORATION
1	PICATINNY ARSENAL	1	WESTINGHOUSE ELECTRIC CORPORATION (NASA)
1	POWER REACTOR DEVELOPMENT COMPANY		
3	PRATT AND WHITNEY AIRCRAFT DIVISION	285	DIVISION OF TECHNICAL INFORMATION EXTENSION
1	PURDUE UNIVERSITY	75	CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION
1	RADIOPTICS, INC.		
1	RAND CORPORATION		
1	REACTIVE METALS, INC.		
1	REACTIVE METALS, INC., ASHTABULA		
1	REHSSFLAER POLYTECHNIC INSTITUTE		